



Developing an Evidence-Based Coexistence Strategy to Promote Human and Wildlife Health in a Biodiverse Agroforest Landscape

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Agroforest mosaics represent one of the most extensive human-impacted terrestrial systems worldwide and play an increasingly critical role in wildlife conservation. In such dynamic shared landscapes, coexistence can be compromised if people view wildlife as a source of infectious disease. A cross-disciplinary One Health knowledge base can help to identify evolving proponents and threats to sustainable coexistence and establish long-term project goals. Building on an existing knowledge base of human-wildlife interactions at Cantanhez National Park (NP), Guinea-Bissau, we developed a causal pathway Theory-of-Change approach in response to a newly identified disease threat of leprosy in the Critically Endangered western chimpanzee (*Pan troglodytes verus*). The goals of our project are to improve knowledge and surveillance of leprosy in humans and wildlife and increase capacity to manage human-wildlife interactions. We describe the core project activities that aim to (1) quantify space use by chimpanzees across Cantanhez NP and determine the distribution of leprosy in chimpanzees; (2) understand the health system and local perceptions of disease; and (3) identify fine-scale risk sites through participatory mapping of resources shared by humans and chimpanzees across target villages. We discuss the development of a biodiversity and health monitoring programme, an evidence-based One Health campaign, and a One Health environmental management plan that incorporates the sharing of space and resources, and the disease implications of human-non-human great ape interactions. We demonstrate the importance of multi-stakeholder engagement, and the development of strategy that fully considers interactions between people, wildlife, and the environment.

Keywords: human-wildlife coexistence, infectious disease, leprosy, One Health, great apes, West Africa, theory of change

INTRODUCTION

With continued human population growth and the associated expansion of human activities, an estimated 95% of Earth's surface has been modified by humans (Kennedy et al., 2020). There is growing recognition that landscapes shared by humans and wildlife, including agroforest mosaics with varying intensity of human activity, will play an increasingly critical role in the conservation of threatened species (Ellis and Ramankutty, 2008; McKinney, 2015). This is of particular importance in the tropics that harbour ~80% of species worldwide and are undergoing rapid environmental change (Döbert et al., 2014; Hockings and McLennan, 2019). In shared landscapes, the urgent need to conserve species that are hovering on the edge of extinction demands the coexistence of people and wildlife, and this poses one of the greatest conservation challenges of the twenty-first century (McLennan et al., 2017; Frank et al., 2019).

Understanding how humans and wildlife use shared landscapes, the nature and implications of their interactions, and how these vary over time, is crucial for developing conservation strategies. Human–wildlife coexistence does not imply the absence of (competitive) interactions or risks, including bi-directional aggression or disease transmission, but negative interactions must remain at a tolerable level to both people and wildlife (Carter and Linnell, 2016). To this end, greater understanding and consideration of the human ecological and socio-political dimension alongside that of wildlife biology are paramount, with conservation strategies ultimately needing to improve the lives of local people (Adams et al., 2004; Dore et al., 2017; Hill et al., 2017; König et al., 2020; Pooley et al., 2020).

Many threatened species are found in tropical countries where a disproportionate amount of people live in poverty. Poverty is not only economic; it encompasses a range of diverse issues including lack of access to healthcare, education, and clean water sources. Conservation programmes that promote coexistence can help to alleviate poverty in rural communities within or adjacent to wildlife habitats. This can be achieved through direct approaches such as helping to secure increased income for rural communities and improving access to healthcare, and indirect approaches such as safeguarding traditional rights, cultural values, ecosystem services, or capacity building of local groups and institutions (United Nations, 2021). For this to succeed, conservationists must work with diverse stakeholders to ensure that conservation approaches are built within a framework that actively incorporates social equity, as well as poverty alleviation and well-being among local communities. Of considerable importance is developing strong working relationships and collaborations amongst local stakeholders such as user groups, youth, student and women's associations, as well as national and international institutions.

INFECTIOUS DISEASE AND ONE HEALTH

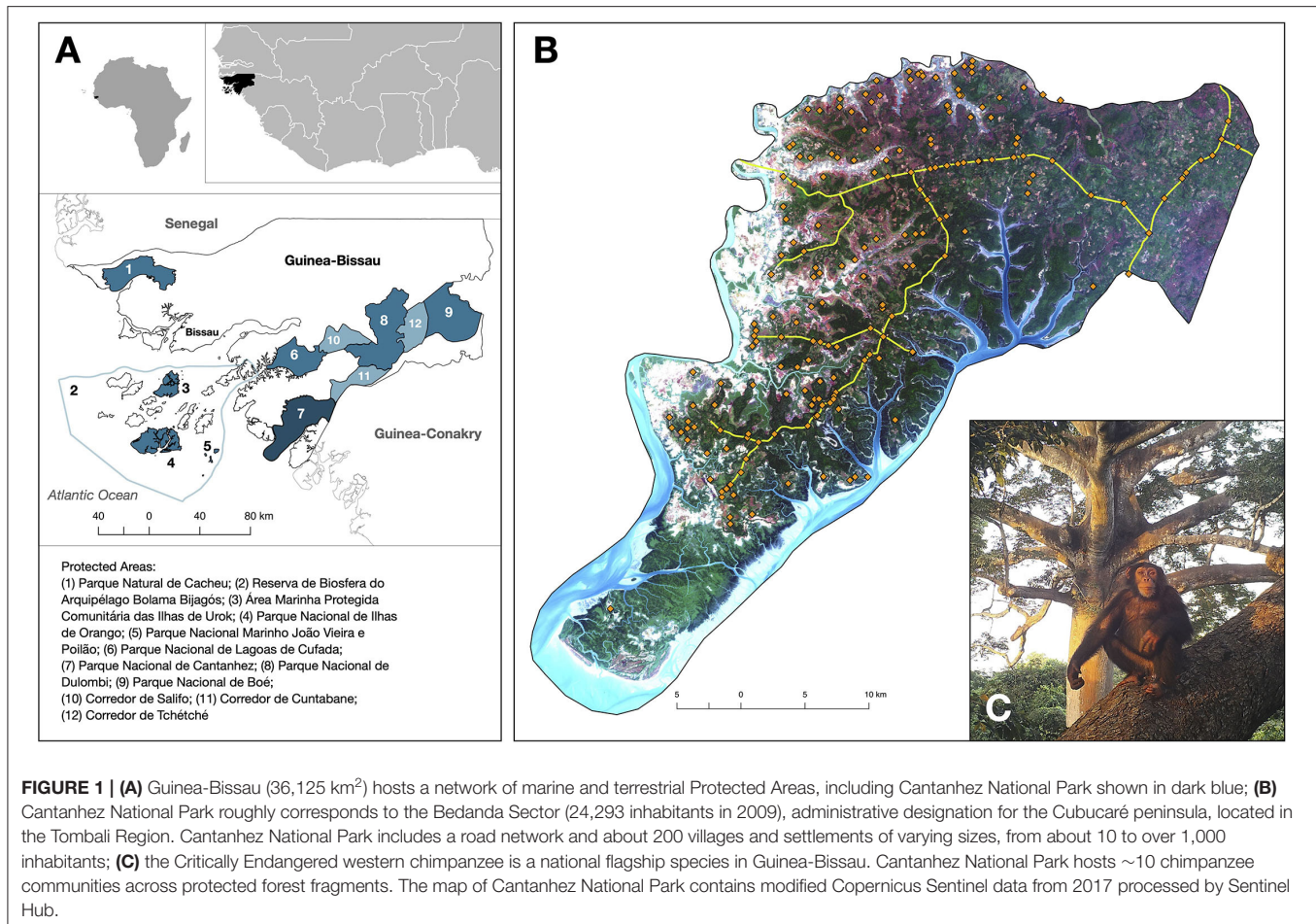
The risk of disease exchange between humans and wildlife means that coexistence can be compromised when people view wildlife as a source of infectious disease and resort to hostile actions (Bicca-Marques and de Freitas, 2010; López-Baucells

et al., 2018; MacFarlane and Rocha, 2020). Infectious disease emergences or re-emergences (i.e., that have either recently appeared or were already present, and which are increasing in incidence or geographic range) are predicted to become more frequent in both humans and wildlife as a result of anthropogenic and environmental changes. Consequently, the potential for cross-species disease transmission to create serious conservation problems, on top of the obvious risks to public health, are also expected to increase. For wildlife, beyond the threats of retaliatory killings by people, there are risks of infection-induced mortality that can arise in two ways. Firstly, zoonotic diseases that are endemic to wildlife and can transmit to humans may become problematic if concurrent threats (e.g., habitat loss by increasing densities or stress) exacerbate infection prevalence and/or severity and lead to disease re-emergence. Such re-emergence could imperil both the animal reservoir species, as well as humans, particularly as habitat destruction, road building and hunting are forcing wildlife into shifting their distributions to utilise human-impacted habitats. Indeed, zoonotic pathogens are thought to have given rise to >60% of known human pathogens, and 75% of emerging infectious diseases in humans to date have a zoonotic origin (Taylor et al., 2001). Secondly, infectious diseases of human origin can emerge in wildlife through spill-overs or host jumps when there is sufficient contact between humans and wildlife. For example, the transmission of metapneumovirus from humans to wild mountain gorillas (*Gorilla beringei beringei*) was shown to be responsible for the death of gorillas in Rwanda in 2011 (Palacios et al., 2011). Because successful pathogen establishment is made more likely by the close phylogenetic proximity between humans and non-human primates (hereafter primates), any increase in human-primate interactions will intensify bidirectional risks of disease exchange (Gillespie et al., 2008). Addressing the issue of disease exchange between humans and wildlife requires adopting a One Health approach which affirms the interconnectedness between people, animals and the environment.

RESPONDING TO A NEWLY IDENTIFIED DISEASE THREAT IN CRITICALLY ENDANGERED WESTERN CHIMPANZEES AT CANTANHEZ NP, GUINEA-BISSAU

Cantanhez NP (1,067 km²), Guinea-Bissau is inhabited by over 24,000 people (Figure 1). Cantanhez NP is characterised by a mosaic of coastal sub-humid forest patches, mangroves, savannah grassland, woodland and agriculture. Since 2013, the Cantanhez Chimpanzee Project has been building a knowledge base of human–wildlife interactions. In 2015, we first observed symptoms of leprosy (*Mycobacterium leprae*) in chimpanzees at Cantanhez NP, with molecular confirmation of *M. leprae* as the causative agent in 2018 (Hockings et al., 2021). This is the first evidence of leprosy in wild nonhuman great apes and in any wildlife in Africa.

Leprosy is a neglected tropical disease, with ~210,000 new human cases reported every year, of which 2.3% are located in West Africa (WHO, 2021a). Leprosy has a long incubation



time of several months to 30 years in humans, with an average of 5 years. Untreated infections result in permanent damage, including an inability to feel pain that leads to a characteristic loss of extremities from repeated injury or infections. Transmission is traditionally believed to occur primarily via aerosolised nasal secretions and entry through nasal or respiratory mucosae, and is therefore considered most common between individuals in close contact (Lastória and Abreu, 2014; Araujo et al., 2016). However, the role of other transmission routes is unclear. *Mycobacterium leprae* can circulate in other animal hosts in the wild, such as the nine-banded armadillos (*Dasypus novemcinctus*) in South and North America and red squirrels (*Sciurus vulgaris*) in the United Kingdom, with the pathogen likely transmitted from humans centuries ago (Hamilton et al., 2008; Sharma et al., 2013; Avanzi et al., 2016). Our recent study on leprosy circulating in wild chimpanzees also suggests environmental reservoirs as potential sources of infection (Hockings et al., 2021).

In response to the detection of leprosy in chimpanzees, and concern that it might result in conflicts with local people, we built on our existing knowledge base to develop a collaborative, cross-disciplinary One Health project. In this paper, we first provide broad context on the social, historical, and biodiversity-rich landscape at Cantanhez NP as a foundation

for understanding human–wildlife coexistence. We then present a causal model to promote public health and conservation and detail project activities, including developing a biodiversity and health monitoring programme; understanding the healthcare structure and its use by the local population; evaluating local knowledge of and perception of disease; and mapping human–wildlife interactions and risk hotspots. We discuss how these activities feed into project outputs to ensure improved knowledge and surveillance of leprosy in humans and wildlife, with enhanced capacity to manage human–wildlife interactions across the landscape. The research involving wildlife and human participants was reviewed and approved by the Ethics Committee of the University of Exeter (Refs: eCORN002520 v3.1 and eCORN002528 v3.1), and human participants provided their informed consent to participate in this study.

UNDERSTANDING HUMAN–WILDLIFE COEXISTENCE IN CANTANHEZ NP

The Social and Historical Landscape of the Cubucaré Peninsula

Guinea-Bissau is a West African country with a diverse ethnic, cultural and religious history. Cantanhez NP is inhabited mostly

by Balanta people, as well as the Nalu, Fulani and Sussu, among many others (Catarino and Palminha, 2018). Over the past decades, populations from different ethnic groups have been moving to this region, mainly from the Republic of Guinea (Temudo and Abrantes, 2014; Parathian et al., 2018). Land use at Cantanhez has changed over time, with the flooded rice culture developed by the Balanta now widely practised (Temudo, 2009). Small-scale production of mango and citrus trees once allowed the natural vegetation to be maintained, with limited deforestation (Temudo, 2009), but from the 1980s onwards the installation of cash fruit crops, including cashew, transformed the landscape for people and wildlife (Temudo and Abrantes, 2014; Havik et al., 2018). With the widescale introduction of fruit crops, frugivores including the chimpanzee, have gradually incorporated these new food sources into their diets, changing the nature of their interactions with people (McLennan and Hockings, 2014; Bessa et al., 2015).

In symbolic and political terms, the inhabitants of Cantanhez NP are divided between the “owners,” the Nalu, founders of the territory, and “guests,” the population of other ethnic groups to whom the Nalu have given permission to settle there. The Nalu have an intricate relationship with the landscape and wildlife. According to Nalu’ pre-Islamic ontology, all beings including supernatural entities, humans, animals and plants, form a system of relations (Frazão-Moreira, 2009, 2015). Within the Nalu territory there are sacred zones that are commonly referred by the Creole term “matu sagrado” (sacred forest). These forests are a landmark of ecological, political and cultural history. The underlying components of a pre-Islamic ontology combined with Muslim beliefs are key to understanding human–chimpanzee coexistence (Sousa and Frazão-Moreira, 2010; Costa et al., 2017). Nalu people have the general belief that all non-human species have reputed access to resources in ancestral lands and the Muslim *aram* prevents the killing and eating of any animal with canine teeth, including primates. The Nalu believe “dari i pekador” (the chimpanzee is human) and acknowledge the physical and behavioural similarities that chimpanzees and humans share (Sousa and Frazão-Moreira, 2010). Animist ontology guides local beliefs that non-human species exist either as true animals, or some other animal form transformed by “irās” (supernatural beings), with humans and chimpanzees being able to shape-shift into each other’s physical forms (Sousa et al., 2017, 2018). Acts perceived negatively by people (such as unprovoked attacks on local persons by chimpanzees) are sometimes attributed to people taking the form of chimpanzees.

In the 1990s, on the initiative of the Non-Government Organisations Acção para o Desenvolvimento, Tiniguena and Alternag, with the support of International Union for Conservation of Nature (IUCN), a project was set up to conserve the remaining forests in the Tombali region, which in 2011 led to the creation of the Cantanhez NP (Figure 1B). Since 2011, Cantanhez NP has been managed by the Institute for Biodiversity and Protected Areas (IBAP) following an IUCN Category V protected area, acknowledging that “the interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural and scenic value: and where safeguarding the integrity of this interaction is

vital to protecting and sustaining the area and its associated nature conservation and other values” (IUCN, 2016). The local management committee (includes 35 people from 14 villages) actively participates in the management of Cantanhez NP which is divided into three zones, including the core zones, largely consisting of protected coastal forest blocks where hunting and logging activities are forbidden, buffer zones, where hunting by local residents is allowed but felling of large trees by residents is subject to permission from IBAP, and agricultural zones (Catarino and Palminha, 2018; IBAP, 2020).

The Environment, Biodiversity and Human–Wildlife Resource Overlap

Guinea-Bissau lies within the Guinean forest-savannah mosaics, a biodiverse ecoregion buffering the Guinean moist forests in the south and the West Sudanian savannah in the north (Figure 1A). The climate in Guinea-Bissau is characterised by a rainy season from mid-May to the end of October and a long dry season from November to mid-May. Cantanhez NP hosts a wealth of wildlife species. Six diurnal primate species are present in Cantanhez NP, including the western chimpanzee (Figure 1C), Temminck’s red colobus (*Piliocolobus badius temminckii*), king colobus (*Colobus polykomos*), Guinea baboon (*Papio papio*), Campbell’s monkey (*Cercopithecus campbelli*) and green monkey (*Chlorocebus sabaeus*). Cantanhez NP is also home to numerous ungulate species including buffalo (*Syncerus caffer*) and bushbuck (*Tragelaphus scriptus*), and biomonitoring efforts have recently confirmed the presence of rare and elusive species, including the African golden cat (*Caracal aurata*), giant pangolin (*Smutsia gigantea*) and in the North of the park, the African elephant (*Loxodonta africana*) (Supplementary Table 1).

As a large-bodied and socio-ecologically flexible species, chimpanzees are able to adapt to complex and dynamic environments, including human-impacted landscapes if they are not hunted (Hockings et al., 2015; Bersacola et al., 2021). At Cantanhez NP, humans and chimpanzees show substantial overlap in their use of space, and encounter each other regularly on roads, paths and around the edges of villages and agricultural areas. Humans and chimpanzees use at least 27 of the same wild fruit species, including oil palm (*Elaeis guineensis*), velvet tamarind (*Dialium guineensis*), and saba (*Saba senegalensis*) (Hockings et al., 2020), with chimpanzee use of space driven partly by the availability of oil-palm fruit (Bersacola et al., 2021). Although the Caiquene-Cadique community of chimpanzees in central Cantanhez NP use areas away from villages and agriculture more intensively, they optimise their foraging strategies when wild fruits are scarce by increasing their use of village areas with cultivated fruits (Bersacola et al., 2021). Despite beliefs that prevent people from hunting chimpanzees and consuming their meat, negative interactions between people and chimpanzees can occur over highly valued crops such as oranges and papaya, with chimpanzees chased and shot at by local people to keep them away from crops during fruiting seasons (Sousa and Frazão-Moreira, 2010). People are more tolerant of chimpanzees foraging on cashew pseudofruit, as the commercially valuable cashew nut remains unharmed. Farmers

perceive that the chimpanzees leave cashew nuts in more manageable piles making harvesting easier (Hockings and Sousa, 2012).

A COLLABORATIVE PLANNING APPROACH TO IMPROVE PUBLIC HEALTH AND PROMOTE BIODIVERSITY CONSERVATION

The development of strategy to help protect threatened species and alleviate poverty in rural communities within or adjacent to wildlife habitats can be challenging. We used a Theory of Change causal model (i.e., an outcomes-based approach to design, implement and evaluate initiatives) to encourage critical thinking and demonstrate linkages between the complex network of factors to promote public health in this biodiverse agroforest landscape (Figure 2). A fundamental part of our project is the consolidation of a multi-stakeholder, cross-disciplinary, multi-institutional collaborative approach to promote conservation and human health in Cantanhez NP.

BIODIVERSITY AND HEALTH MONITORING PROGRAMME

Measuring Chimpanzee Distribution and Intensity of Space Use

As part of the Biodiversity and Health Monitoring Programme (BHMP), we established transect routes and camera trap sampling points across Cantanhez NP in December 2019 (Supplementary Figure 1). Transects and camera traps covered habitat types across the landscape mosaic, including secondary forest, woodland, mangroves, orchards, shifting cultivation fields, villages, roads and remnant forest strips dominated by oil palms. We carried out monthly transect surveys using Cybertracker and checked camera traps monthly. We conducted distance sampling along line transects and recorded chimpanzee nests, direct encounters with wildlife, and animal and human signs, following standardised protocols (Buckland et al., 2015).

As of March 2021, biomonitoring surveys consisted of 400 km of transect survey effort and 11,884 camera trap days across 13 protected forest blocks and surrounding agro-forest mosaics. Supplementary Table 1 shows the confirmed presence of all wildlife species recorded during surveys. Chimpanzees are distributed across the park, with nests recorded in 44% of the transects. Nests were observed more frequently across the central part of Cantanhez NP (86%, of total N of nest observations = 72), where sub-humid forest cover is more extensive compared to the drier savannah-woodland-forest mosaic in the northern part. We analysed camera trap data collected during the first biomonitoring season between January and July 2020 (7,514 camera trap days). We extracted 901 independent events for chimpanzees, defined as images or sequences of images at least 60 mins apart from the previous images of the same species at the same location. We employed Bayesian spatial modelling and extracted a prediction map for intensity of space use by

chimpanzees across Cantanhez NP (Figure 3A, see figure caption for more details on the analysis).

Monitoring Leprosy in Chimpanzees

We first observed clinical signs of leprosy in chimpanzees through the analysis of camera trap data in 2015. We then conducted molecular analyses of chimpanzee faecal samples and confirmed *M. leprae* as the causative agent of the lesions observed in chimpanzees (see Hockings et al., 2021, for details). From 2015 to 2021, we were able to determine the occurrence of advanced leprosy (multibacillary) in five chimpanzee communities across the park, with *M. leprae* likely transmitted between individuals within this population. We identified seven affected individuals (three adult females, two adult males and two adults of unconfirmed sex), and possible cases of leprosy in three other individuals. Advanced leprosy symptoms in chimpanzees include hair loss, plaques and nodules that cover different areas of their body (limbs, trunk and genitals), facial skin hypopigmentation, facial disfigurement as well as ulcerated and deformed hands (claw hand) and feet (Hockings et al., 2021) (Figure 3B). Paucibacillary cases in chimpanzees, where bacterial levels are low, can easily go undetected as minor physical manifestations of leprosy such as localised hair loss are challenging to observe on camera trap footage. Data collection using additional camera traps in affected chimpanzee communities, as well as faecal sampling for determining the prevalence of leprosy in chimpanzees are ongoing. These long-term data allow us to determine changes in physical symptoms displayed by individuals over time and any changes in community prevalence of the disease.

HUMAN DIMENSIONS OF HEALTH

The Health System in Guinea-Bissau

Guinea-Bissau is strongly dependent on agriculture and fisheries and is among the poorest countries on Earth, with 67% population living below \$1.90 USD/day. The health sector in Guinea-Bissau suffers from a lack of financial and material resources, as well as a lack of specialised human resources (Guerreiro et al., 2017, 2018a,b; Russo et al., 2017; Guerreiro, 2019). The national health system is organised into three levels: central, regional and local (Supplementary Table 2). In 2017, 66% of the population did not have geographic access to services, i.e., they live beyond 5 km from the nearest primary health care delivery structure (Guerreiro et al., 2017). According to the latest available data, in 2016, the number of doctors stood at 1.3 per 10,000 people, and the number of nurses and midwifery personnel at 5.9 per 10,000 people (WHO, 2021b). At regional and local levels, there are also some health facilities under the responsibility of non-governmental, religious or other organisations.

Leprosy Strategies and Treatment

The government of Guinea-Bissau has established sectoral action plans, following World Health Organization (WHO) guidelines. These include the Master Plan for the Control of Neglected Tropical Diseases in Guinea Bissau, which takes

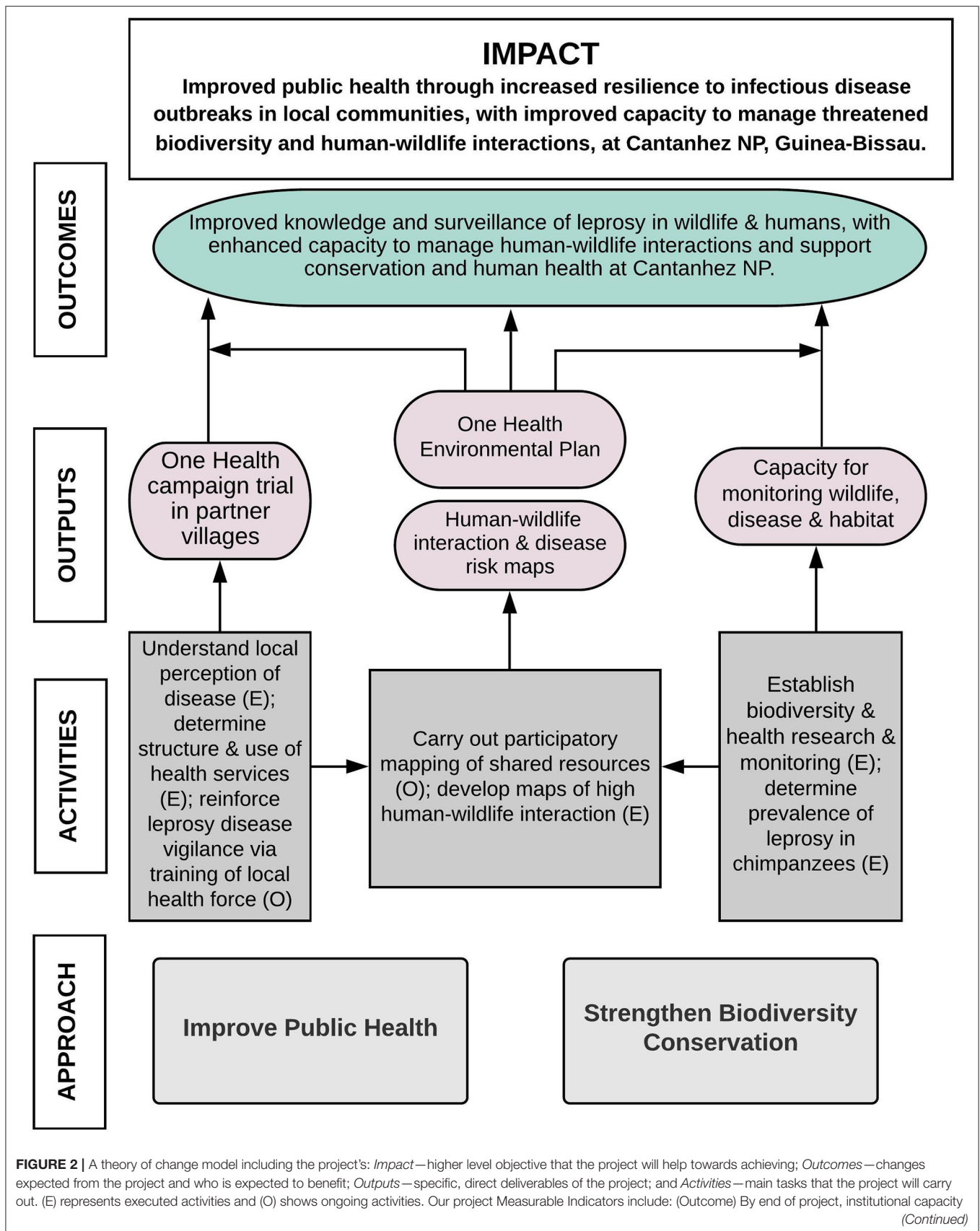


FIGURE 2 | to monitor disease in wildlife in Cantanhez NP is increased to 80% compared to baseline (zero) through the implementation of biodiversity monitoring and the establishment of an IBAP surveillance team for sample collection and management of animal carcasses; (Output 1—Health Campaign) By the end of Year 3, at least 50% of campaign participants ($N = 30$ out of 60, including at least 50% women) demonstrate increased understanding in the links between environmental, animal and human health via One Health trial campaign in six partner villages compared to baseline pre-campaign; (Output 2—BHMP) By Year 2, the wildlife monitoring capacity in Cantanhez NP is increased to 80% compared to baseline 5% (based on number of park staff trained to record and analyse data, and existing training manuals); (Output 3—One Health plan) By the middle of Year 3, key wildlife habitat including corridors, and areas of high human–wildlife interaction and potential disease transmission are identified, and; by the end of Year 3, the plan is developed with stakeholders (Management Committee and other group representatives including from the Cantanhez Women's Associations) comprising at least 50% women; (Output 4—Leprosy response plan) By the end of Year 3, institutional capacity to sample, handle and dispose wild animal carcasses securely is increased by 100% compared to baseline zero; By Year 4, institutional knowledge to manage and respond to conflicts over leprosy disease (including mistrust of health services, retaliatory behaviour towards animals) and leprosy in humans is increased via the production of the first multi-stakeholder leprosy response plan in Guinea-Bissau. This project includes different health and conservation partner Institutions and Organisations in Guinea-Bissau, including the Institute for Biodiversity and Protected Areas, (IBAP), the Associação Nacional para o Desenvolvimento Local e Urbano (NADEL), and in Europe, including the University of Exeter in the United Kingdom, the Centre for Research in Anthropology in Portugal, and the Robert Koch Institute in Germany. Local partners include the women's groups and the local management committee, which is actively involved in the management of the park alongside IBAP.

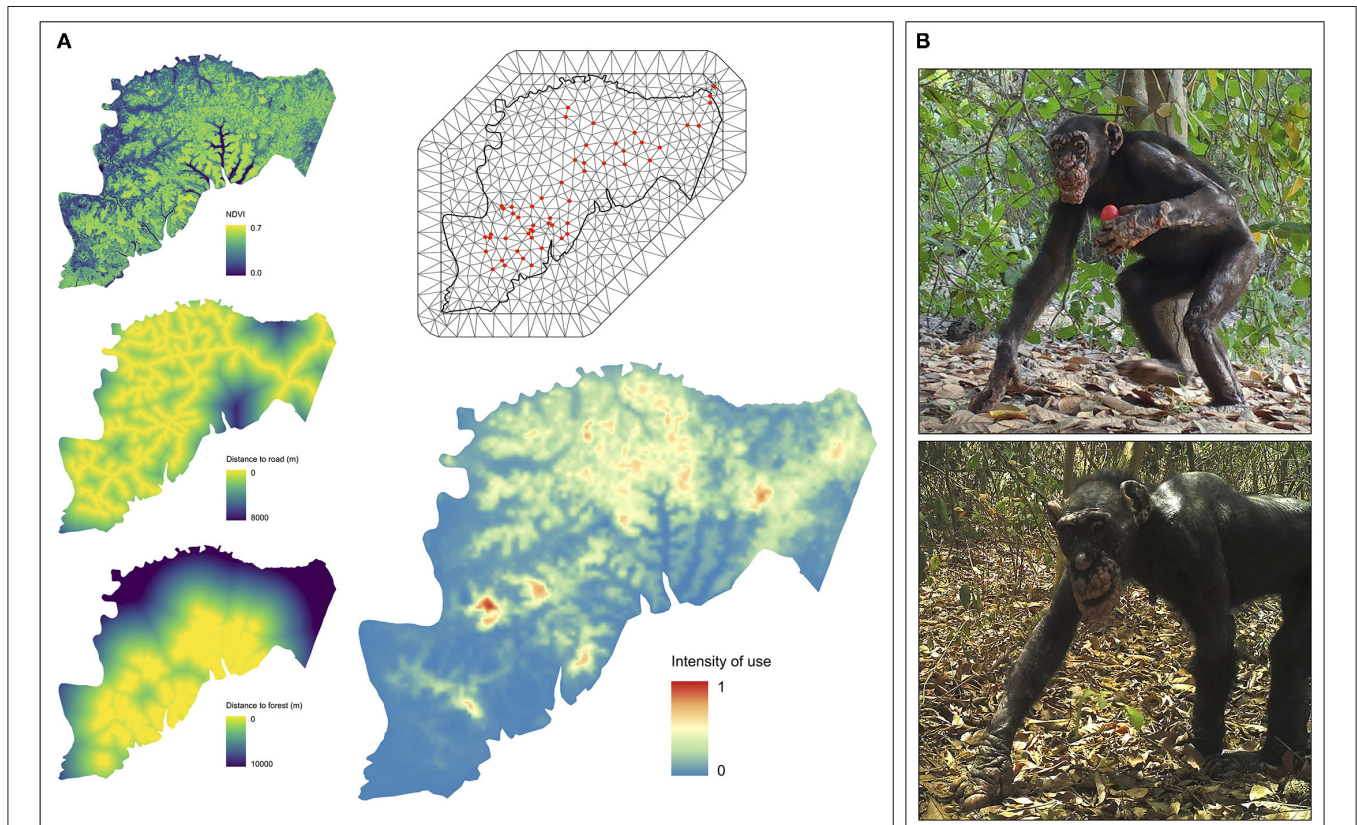


FIGURE 3 | Summary of results based on camera trap data from the first season of the biodiversity monitoring programme in Cantanhez NP. **(A)** Camera trap data were analysed to determine intensity of space use by chimpanzees. We employed Bayesian spatial modelling using the Integrated Nested Laplace Approximation (INLA) with Stochastic Partial Differential Equation (SPDE) approach (Lindgren et al., 2011; Rue et al., 2009) using the R-INLA package on R (Blangiardo et al., 2013; Blangiardo and Cameletti, 2015; R Core Team, 2020). Since its recent inception, this efficient statistical framework has become established across various scientific disciplines (Rue et al., 2017; Bakka et al., 2018) including wildlife ecology (e.g., Lezama-Ochoa et al., 2020). Its applicability to camera trap-based ecological research has also been recently demonstrated (Bersacola et al., 2021). Our model included seven covariates, including normalised difference vegetation index (NDVI), calculated from Sentinel-2 imagery dated 29 February 2020, as well as linear distance to the nearest protected forest block, distance to the nearest village, distance to large roads (newly improved 10 m-wide gravel roads) and distance to all roads (including small rural roads). Latitude and longitude were also included as covariates. This modelling framework uses a triangulation mesh of the study area to estimate the spatial autocorrelation amongst the sampling points and allows for the estimation of geostatistical data across a continuous field (interpolation). Bottom right shows the output map of the selected Binomial-SPDE model for chimpanzees, with the response variable constituting intensity of space use by chimpanzees at Cantanhez NP, represented by the sum of the number of occasions with positive detection (y) relative to the total number of sampling occasions (number of trials). **(B)** Two of the identified advanced leprosy cases in chimpanzees in Cantanhez NP, from top to bottom showing “Rita”, an adult female from the Caiquene-Cadique community diagnosed with advanced leprosy based on camera trap footage and confirmed through molecular analysis in her chimpanzee community, and “Cristina”, an adult female from the Faro Sadjuma community, with her diagnosis based on physical symptoms.

into consideration 13 priority diseases in Africa, including leprosy, and the National Tuberculosis and Leprosy Control Programme (MINSAP, 2014). Leprosy, according to the criteria of the WHO, is considered to be eliminated at the national level in Guinea-Bissau, because the number of patients on multidrug therapy is <1 case per 10,000 inhabitants (a value considered as the elimination target by the WHO). Nevertheless, leprosy is endemic with official figures showing between 50 and 70 new cases of leprosy detected each year (MINSAP, 2014). Importantly, not all cases of leprosy are identified; in its early stages the disease is easily confused with other conditions.

Cumura Hospital, located near Bissau, is the only health structure dedicated to the treatment of leprosy in Guinea-Bissau. It was founded in 1952 with the support of Catholic missionaries (particularly Italian Franciscan missionaries) to isolate leprosy patients, according to the medical knowledge of the time and the stigmatisation of the disease (Costa, 2010). Nowadays, the Cumura Hospital is managed by the Catholic Mission of Cumura and funded by the NGO AIFO (Amici di Raoul Follereau), following international scientific procedures concerning leprosy. Patients are mainly treated on an outpatient basis, although Cumura remains a permanent residence for some leprosy patients with disabilities. Beyond hospital work, the Cumura team has trained some nurses and community health agents. Cumura Hospital has treated patients from the Tombali region, although we do not currently have reliable counts of people with leprosy in Cantanhez NP. The population of Cantanhez NP locally receives support from “Type C” health centres (Supplementary Table 2), as well as from health facilities belonging to religious missionaries. If a patient with suspected leprosy is identified by a community health agent, the agent directs the patient to a “Type C” health centre. If treatment cannot be carried out there, the patient is directed to a “Type B” health centre at Cacine or Quebo, or to the Catió Regional Hospital. If a suspected leprosy case is identified, the patient should expect to be referred to Cumura Hospital.

Traditional medicinal systems are also present in Guinea-Bissau and are particularly important in contexts where the public health system is lacking or inefficient. In these systems, medicine cannot be dissociated from ontology and religious dimensions. In Cantanhez NP, there are various types of traditional healers: *curandeiros* (healers who can be from any ethnic group with different religions), *djambakus* (healers that perform divination and ritualised treatments based on traditional and pre-islamic Nalu beliefs), and *marabouts* (Muslim medicine-men). Healers have a refined knowledge of medicinal plants and treatments (Frazão-Moreira, 2009, 2016; Catarino et al., 2016). Patients consult these healers, seeking explanations for their health problem and its cure, either before going to the health centre or at the same time as consultations with nurses or doctors. Here, as in other parts of Africa, treatment itineraries are complementary and simultaneous, and are not culturally perceived as contradictory (Augé, 1984; Janzen and Green, 2003; Ribera, 2007).

LOCAL KNOWLEDGE OF LEPROSY AND ONE HEALTH

We conducted semi-structured questionnaires (Bernard, 1995; Kvale, 1996; Weller, 2015) with 92 participants including residents, healers and health workers across Cantanhez NP to identify local knowledge on leprosy transmission, diagnosis, and treatment (Figure 4, see figure caption for more details on methods). To help inform the development of a One-Health strategy, we conducted interviews with another 50 residents to understand perceptions and mitigation of risks of infectious disease transmission and barriers when accessing healthcare. In Cantanhez NP, leprosy is known by local people, but knowledge of symptoms, causes and transmission is limited, particularly at its early stage (Figure 4A). There was a lack of knowledge by both healers and health workers on how to treat leprosy and which health facilities to direct suspected leprosy patients, including no knowledge of the specialist leprosy hospital, Cumura. Zoonotic disease transmission is an issue that people show little awareness of, although there is some knowledge of factors that might increase the risk of zoonotic disease transmission including the consumption of fruit that an infected animal has touched, the consumption of meat from a sick animal, and the use of shared water sources. Many people, but not all, perceive wildlife carcasses as possible disease risks. To avoid disease transmission, people suggest maintaining a distance and not touching the carcass. However, perceptions of what to do in the event of encountering a sick wild animal vary (Figure 4B). Most people said they would go to a hospital or a health centre if they become ill, with some also visiting healers. However, people experience difficulties (from a lack of finances, shortage of medication at the health centre/hospital, and a lack of transport) when trying to access medical help (Figure 4C).

MAPPING HUMAN-WILDLIFE INTERACTIONS AND RISK HOTSPOTS

Human, chimpanzee and environmental data are combined to identify areas of high spatial overlap between humans and chimpanzees, with increased likelihood of negative interactions (Figure 5). At the landscape level, risk areas constitute all areas where chimpanzees are recorded using space more intensively (Figure 5A) including villages and settlements within that territory. At the fine scale, risk sites constitute sites where people share resources with chimpanzees, including water, human crops and wild foods (Figure 5B).

DEVELOPING EVIDENCE-BASED OUTPUTS

Public Health Campaign and Clinical Training

COVID-19 and Ebola health campaigns are being conducted across Guinea-Bissau, including in Cantanhez NP. To avoid campaigning about another infectious disease, leprosy, and risking low engagement with local communities, we chose to

A Local knowledge about leprosy

51% (26 of 51) of **local people** said they **have never seen it**

67% (34 of 51) were **unfamiliar with the symptoms**

92% (47 of 51) **did not know how it is transmitted**

Health workers

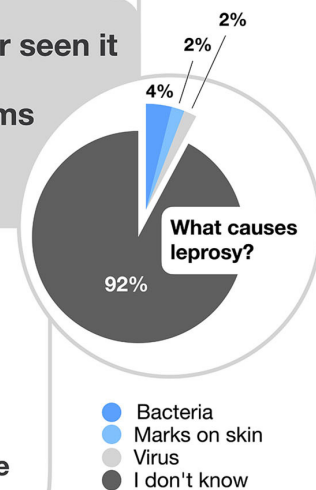
Only 1 of 5 nurses identified leprosy in its early stage

Of the 4 nurses who identified leprosy in its advanced stages, none were able to suggest treatment options

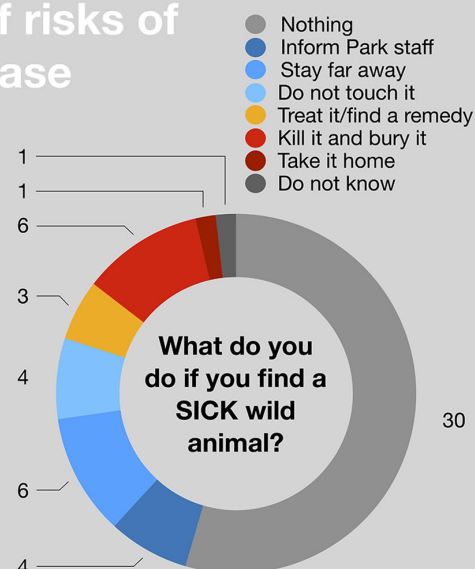
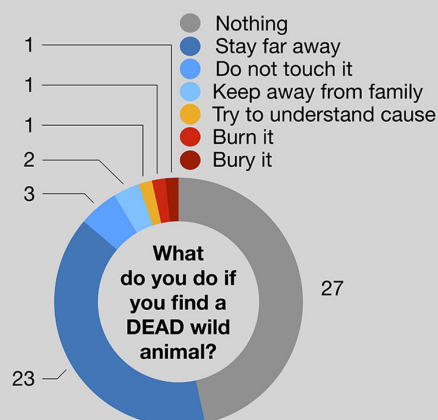
Traditional healers

None of the healers could identify leprosy in its early stage

3 of 5 healers recognised leprosy at its advanced stages



B Local perceptions of risks of animal-to-human disease transmission



C Access to healthcare

86% (43 of 50) of participants **reported difficulties** when trying to access medical help at a health centre or hospital

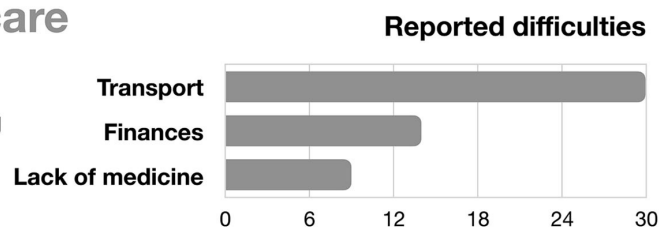
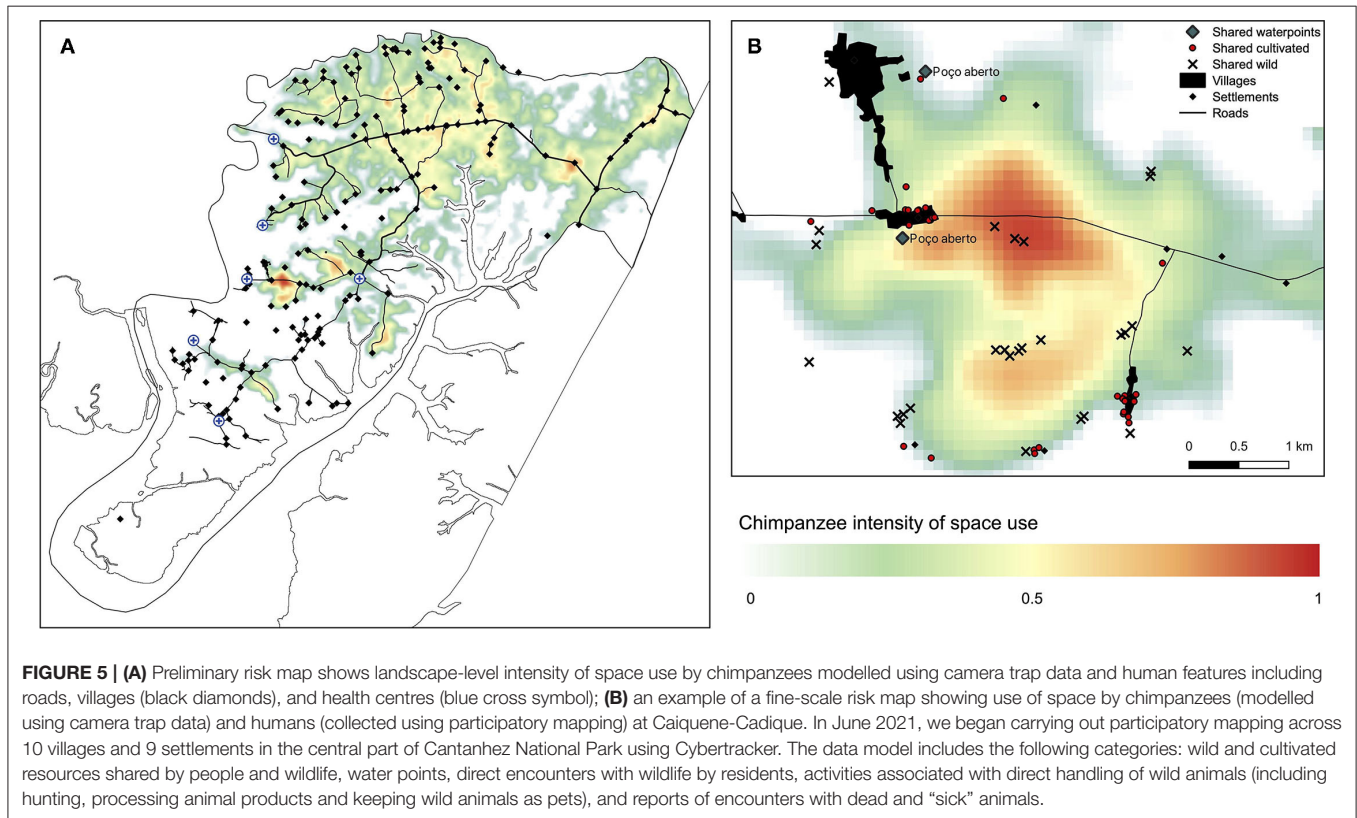


FIGURE 4 | Summary of results from interviews conducted across 27 villages in Cantanhez NP, to **(A)** understand local knowledge of disease including leprosy (51 household participants, five health workers and five traditional healers); **(B)** local perceptions of disease transmission risks (50 household participants); and **(C)** reported problems when attempting to access health care in Cantanhez NP (50 household participants). Values in sections **(B,C)**

(Continued)

FIGURE 4 | represent number of reported actions or difficulties, with some participants reporting more than one. Interviews were conducted in March and December 2020. We first piloted a semi-structured questionnaire with 31 participants across 13 villages, which included listing known infectious diseases and asking participants to describe symptoms, causes and treatment, as well as questions about disease in animals. To gather a knowledge baseline about leprosy, we subsequently conducted interviews across 27 villages, asking more specific questions about leprosy. For these we employed three semi-structured questionnaires: one for the general public ($n = 51$ participants), one for traditional healers ($n = 5$) and one for health workers ($n = 5$). To understand perceptions and mitigation of risks of infectious disease transmission and barriers when accessing healthcare, we employed a separate semi-structure questionnaire with 50 participants. We interviewed a total of 142 people, including 68 women and 74 men, from 10 ethnicities, including Nalu, Fula, Balanta, Tanda, Sussu, Djacanca, Pepel, Beafada, Bijagos, Mandinka.



develop a campaign to publicise One Health messages more broadly with leprosy used as one example of possible zoonotic infection. Delivering One Health concepts is complex; to reduce the risks of miscommunication regarding the disease threat posed by wildlife and the possible dangers to human health, we opted to reduce the geographical scale of the campaign to initially trial messages in selected villages. The focus on only six selected villages enables us to explore and identify effective ways to deliver One Health messages which will be incorporated into a One Health campaign strategy report for future application. Pre- and post-campaign interview questionnaires with participants from the selected villages will be used to evaluate changes in understanding of the links between environmental, animal and human health (see Measurable Indicator for Output 1, **Figure 2** caption). Additionally, working alongside Cumura hospital and AIFO, we will involve health workers as well as local health agents and healers in clinical training to identify all stages of leprosy disease with clear instructions for the referral protocol.

Biodiversity and Health Monitoring Programme

The BHMP has achieved increased wildlife monitoring capacity in Cantanhez NP through intensive training of local staff in data collection, including deploying and maintaining camera traps, recording direct and indirect animal observations and measuring habitat type using datasheets, GPS and Cybertracker. Guinean researchers are trained in data entry, management and analysis to ensure the sustainability of the monitoring programme. To promote good practise, staff have received training in the necessary health precautions during data collection.

One Health Environmental Management Plan

A One Health environmental management plan will promote healthy human–wildlife coexistence and strengthen multi-stakeholder decision-making capacity in Cantanhez NP. The plan aims to reduce possible risks of disease transmission within and

between-species and to inform future management strategies, including replanting and re-organising chimpanzee food sources across risk areas to reduce spatial overlap and conflicts. Key wildlife habitat and corridors, as well as areas of high human–wildlife interactions and potential disease transmissions are identified (see Measurable Indicator for Output 3, **Figure 2** caption) using data from the BHMP and participatory mapping. With additional GIS layers, including 2017–2021 vegetation cover and health landmarks (graded health centres, health units, healers), these data will help inform the development of the plan. Maps will be shown and discussed during meetings with local stakeholders, including the management committee, women's groups, farmers, and hunters. Maps will also be discussed with local people to identify aspects of human–wildlife interactions related to One Health that will need to be taken into consideration, such as sites where resources are shared (water points, cultivated foods). We use this opportunity to ask people to propose measures to minimise contact with wildlife. These meetings will be used to inform the content of the One Health environmental management plan.

Multi-Stakeholder Leprosy Response Plan

An effective infectious disease response plan requires coordination, communication and collaboration amongst conservation and health stakeholders. An increase in multi-stakeholder knowledge of leprosy occurrence in humans in Cantanhez NP and how to respond to conservation conflicts over disease will be achieved through multi-stakeholder collaboration in developing a leprosy response plan. The plan will be developed from published literature, knowledge exchange between project partners, including consideration of the socio-political context in Cantanhez NP, and the revision and development of a communication chain from local to national level (Cumura Hospital) and WHO. To reduce the risk of pathogen transmission and increase scientific knowledge on other infectious diseases present in Cantanhez NP, the response plan also involves the development and implementation of a protocol for the handling and management of dead chimpanzees and other wildlife. The plan will involve establishing a communication chain for when animal carcasses are found in the forest or information is received about a retaliatory wildlife killing. Information will need to be shared from residents to park guards, and then to IBAP managers and the Cantanhez Chimpanzee Project. Carcass swabbing, which involves taking biological samples from a carcass by inserting a sterile swab into natural body orifices or wounds, will then be carried out exclusively by trained staff using the appropriate PPE (FFP3 mask, goggles, and gloves). A detailed protocol for data and sample collection, decontamination, and waste disposal will be followed.

DISCUSSION

This project integrates biodiversity conservation and public health in response to the identification of leprosy in Critically Endangered chimpanzees and adopts a One Health approach to understand and tackle infectious diseases. Our causal pathway

approach helped our team to identify our long-term One Health goals at Cantanhez NP and the conditions needed to achieve those goals, leading to better planning. Maintaining and strengthening the collaborative environment for project partners has been crucial for every aspect of this project. By investing in capacity and engagement of local communities and partners our goal is to strengthen the sustainability of the work. Our activities are designed to increase future resilience through training and capacity building so that in the potential absence of future funding, Bissau-Guinean partners and local collaborators have a strengthened knowledge base from which to build and continue key activities. From the outset we have ensured participatory community involvement in public health issues to reduce gender inequality, and strengthen synergy in stakeholder (local communities, Government, NGO) decision-making, and this will be an ongoing process.

Our project tackles many of the major challenges outlined in the WHO Global Leprosy Strategy 2021–2030, including cutting-edge research on wildlife and human dimensions of leprosy; reducing delays in detection; strengthening capacity and leprosy expertise; ensuring meaningful engagement of relevant stakeholders; reducing stigma in healthcare settings through knowledge and training; developing a communication and surveillance system; and providing suggestions for information systems to report leprosy cases. In particular, the strategy states that zoonotic transmission of leprosy until now appears to be low risk and highly localised. Our research provides up-to-date information on leprosy in human's closest living relative, the chimpanzee. Our ongoing work will provide key information on the potential for leprosy transmission and exchange between humans and wildlife, and between different wildlife species. Ultimately, successful, sustained, and effective disease control is likely to require more generalised poverty reduction and health capacity strengthening operations in affected nations. Applying a One Health approach, by tackling the interconnected threats to community and ecosystem health, has huge potential to advance responses to community and ecological health threats, mitigate conflict and limit the risk of infectious disease and its transmission.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of the University of Exeter Ref eCORN002528 v3.1. Verbal consent was obtained from interview participants, but written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. The animal study was reviewed and approved by Ethics Committee of the University of Exeter Ref eCORN002520 v3.1.

AUTHOR CONTRIBUTIONS

All co-authors contributed to the development of the concepts presented in the paper and discussed and developed the Project Outputs. Data were collected by EB, MJ, AS, SC, SQ, and AL with support from KH, HP, AF-M, AR, ARS, QQ, SJ, LP, MR, JB, BG, CB, and FL. Data were analysed by EB, HP, AF-M, MJ, AS, and KH. EB and KH led on the writing of the manuscript, supported by all co-authors. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fcsc.2021.735367/full#supplementary-material>

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